VR-in-a-Box: Surgical Simulator - Supplementing Surgical Training for medical students using a low-cost virtual reality simulator with real-time haptic feedback

Final Report

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Team

Principal Investigators

Ayanna M. Howard, Ph.D., Georgia Institute of Technology

Kenneth L. Wilson, MD, FACS, Morehouse School of Medicine, Grady Memorial Hospital

(Affiliate) *Jayfus Doswell, Ph.D.,* Juxtopia, LLC

Post-doctoral Scientist: Chung Hyuk Park

Undergraduate Student: Tiffanie R. Smith

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I. INTRODUCTION

In recent years, there has been a verifiable increase in the use of virtual reality (VR) simulation technology for clinical purposes. Although results are varied, studies have shown evidence that the use of VR in surgical training results in improvement in practicing surgical skills. Unfortunately, such simulators are expensive and thus are not targeted for use by student populations outside of their training facility. Yet, given the current climate of budget reductions and reduced allocations to aid hospitals to pay for training of new residents and medical students, the development of effective, but low-cost training options, is no longer a luxury, but a necessity. This is especially true given that currently mandated restrictions on the maximum hours in which a resident can participate in clinical activities correspondingly decreases exposure to the number of operations performed by general surgery residents. As such, for this research, we have designed a low-cost VR surgical simulator for training medical students and have evaluated its usefulness by examining its learning effects in a pilot study with six students. The results from this study are designed to provide preliminary evidence on the efficacy of a low-cost VR surgical training system by comparing the increase in skill learning using the VR training system. This research lays the preliminary groundwork for designing a low-cost virtual reality system for individualizing the learning cycle to improve surgical skills training through adaptation, human observation, and feedback.

II. SPECIFIC AIM

Virtual reality (VR) surgical training systems seem to be a potentially useful method for improving practicing surgical skills [1-3]. However, the current literature on VR training has not discussed the efficacy of VR systems that are useful outside of the training facility. As such, the goal of this study is to evaluate the benefits of using a low-cost VR simulation system for providing a method to increase the learning of surgical skills. Our pilot case focuses on laparoscopic cholecystectomy, which is one of the most common surgeries currently performed in the United States and is often used as the *training case* for laparoscopy due to its high frequency and perceived low risk. The specific aim of this study is:

- To examine the efficacy of a low-cost VR surgical simulator on improving practicing surgical skills, measured by the change in the learning effect of students.

III. BACKGROUND AND SIGNIFICANCE

A. Laparoscopic cholecystectomy

Laparoscopic cholecystectomy is one of the most common surgeries currently performed in the United States and is often used as the *training case* for laparoscopy due to its high frequency and perceived low risk. Since its introduction to surgery in the 1980s, the laparoscopic removal of a diseased gallbladder (laparoscopic cholecystectomy) has become the gold-standard [4]. It is the most commonly performed elective abdominal procedure in the United States. However, the performance of this procedure can be technically challenging, and injuries occur in 1 of 200 laparoscopic cholecystectomies performed by experienced surgeons. Common bile duct injuries, which affects the body's ability to drain bile from the liver into the gastrointestinal system, is the leading cost of medical malpractice cases filed against general surgeons. In addition, patients who have sustained common bile duct injuries during the performance of laparoscopic cholecystectomies are susceptible to complex repairs by hepatobiliary specialists and can become extremely ill or die.

The present instructional method for learning laparoscopic surgery involves an apprenticeship to a senior surgeon. Studies have shown that additional training, beyond the hours of initial guidance, is a necessary component for establishing expertise [5]. For example, in the study discussed in [6], surgeons who did not have additional training after completing an 18-day training seminar were 3.39 times *more* likely to have at least one complication than those surgeons who had additional training. In [7], it was shown that the chances of a bile duct injury conducted by an experienced surgeon decreased from 1.7% during the first case to .17% after 50 cases. And [8] documents that 90% of bile duct injuries occur within the first thirty cases performed by a practicing surgeon.

B. Effect of Virtual Reality (VR) on Surgical Skills

Virtual reality simulators enable the creation of interactive 3D environments within which human performance can be motivated, recorded, and measured. Nearly a decade ago, Satava [9] first proposed using these virtual reality environments in the training of surgical skills. Although results are varied, studies have shown evidence that VR training results in technical skills acquisition is at least as good as, if not better than, traditional residency training [1-3]. Unfortunately, VR simulators for laparoscopy and colonoscopy training have been reported as still too expensive [10]. Costs of simulation systems were documented as ranging from $5K for most laparoscopic simulators to approximately $200K for highly sophisticated anesthesia simulators. As such, although, based on published studies, VR seems to be a promising tool to use in training and improving surgical skills, there is still a lack of studies evaluating the effect of low-cost VR systems outside of the training facility.

The most promising "low cost" laparoscopic simulator that is currently in use and being used to measure technical skills in simulated training is the McGill Inanimate System for Training and Evaluation of Laparoscopic Skills or MISTELS. The MISTELS system features a trainer box with two 12 millimeter trocars placed on the sides of a laparoscope. Optically, the system consists of the laparoscope, a camera, a light source and a monitor. A current adaption of the original MISTELS system can be seen in Figure 1. The system was used to test selected students in five different tasks, including peg transfer, pattern cutting and creating an extracorporeal knot, that were first demonstrated to them via videotape. After a series of tests, the MISTELS proved that the skills of the students increased after using the simulator. These results concur with other tests proving VR simulation to be beneficial to medical training. Unlike the other studies, this MISTELS system asserts itself on being inexpensive. In comparison with the higher end $200,000 anesthesia simulator, this particular simulator is fairly cheap. The version seen in Figure 1 is priced at $1,680.00 (not including the display monitor). With budget reductions, even this "low cost" simulator may not be practical though for utilization in abundance outside of the training facility.

Figure 1. MISTELS system

IV. SYSTEM DESIGN

The most important goal of any training method is to increase the level of skill that can be brought to bear on a clinical situation. To enable simulation of such procedures as laparoscopic cholecystectomy, the designed virtual training system must employ the same ergonomics applicable to laparoscopic surgery while teaching appropriate muscle memory for the safe performance of a laparoscopic cholecystectomy. As such, our ***VR-in-a-Box: Surgical Simulator System*** consists of 1) a virtual environment for emulating patient-specific anatomy and surgical instrument interaction, 2) motion sensors for tracking and assessment of the student's hand and arm motions for control of the VR surgical instruments, and 3) haptic feedback devices for providing feedback during achievement of the surgical operation.

VR Environment: We developed two prototypes of the VR-in-a-Box: Surgical Simulator (Figure 2). Studies conducted using the first prototype informed the design of the final VR system. Details on each of these versions are provided in the next section.

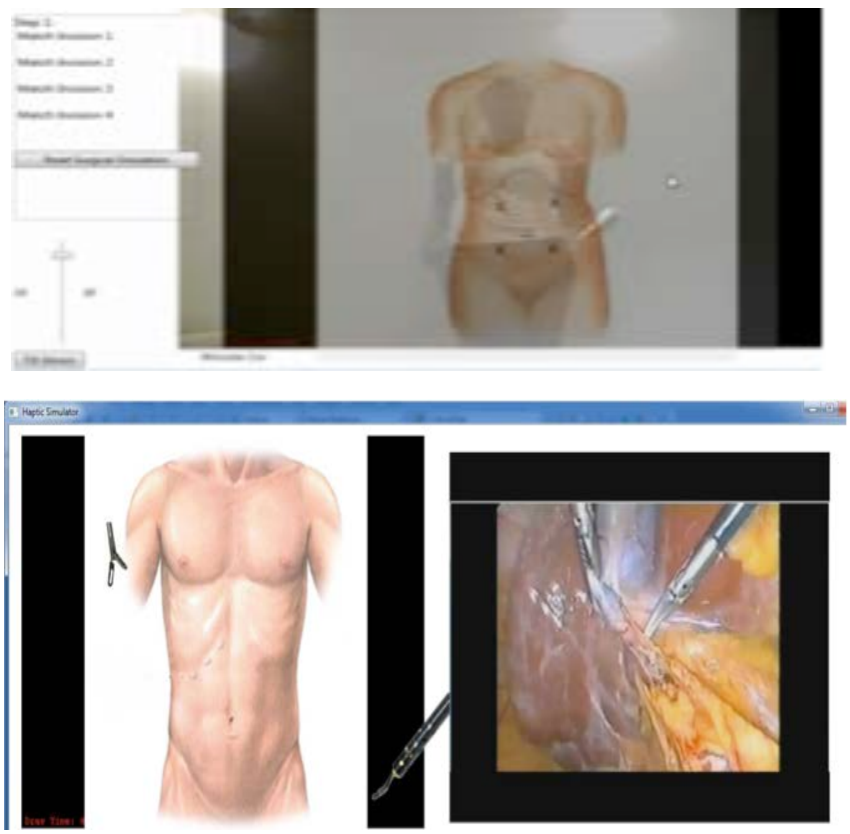


Figure 2. (Top) Snapshot of first prototype, (Bottom) Snapshot of the final design of VR-in-a-Box.

Motion Sensors: A 3D depth camera is a sensor that can be used to capture and store information associated with a user's body movements. This research used the Microsoft Kinect 3D camera because of its low-cost and widespread adoption. Kinect's motion sensors enable the control of virtual reality *characters* through a user's own movements and gestures. Using these low-costs sensors, our VR environment can be turned into a virtual operating room in which student's arm and hand movements can control the VR surgical instruments (Figure 3). This involves obtaining joint angles from the user and applying them to control the virtual versions of the surgical tools.

Haptic Feedback: Haptic feedback provides a means to associate non-visual feedback to a user based on correct (or incorrect behavior). In prior work, we have shown that haptic feedback is an important mechanism for transferring motor skills between expert and novice users [11]. For this research, we utilized a Wii remote controller (Wiimote) for haptic feedback. The Wiimote is a low-cost interactive game controller that has several buttons for input and a motor for creating a vibration. This is a highly portable device and, with Bluetooth connectivity, allows serial communication with any paired computing platform. Haptic feedback is provided by coding functions that modulate the strength and duration of the Wiimote vibrations associated with the type of feedback needed. In our pilot study, haptic feedback is provided to the student by correlating haptic response to correct (or incorrect) steps identified by evaluating surgical instrument interactions with the virtual environment.

Figure 3. Student interacting with the VR-system using the Kinect motion sensors and Wiimote

A. VR-in-a-Box: Surgical Simulator – First Prototype

To develop a low-cost system for the training of cholecystectomy surgical operation in an efficient manner, we designed a multi-modal interactive system composed of a computer, Kinect sensor, and a Wiimote. This system is designed to 1) display graphic-user-interface (GUI) with medical contents for training and/or evaluation of the skill level of the student, 2) monitor the user's movement and overlay surgical tools on the GUI to simulate the use of surgical tools in a virtual surgical environment, and 3) evaluate the user's movement and determine the user's progress in learning the steps of the cholecystectomy surgery.

To design the initial prototype, we first documented the steps of two training videos typically provided to novice medical students: LaparoscpicSurgery.mov and Cholecystectomy.mp4 (www.medicallegalart.com). These video tutorials provide the general concepts and basic steps for Laparoscopic cholecystectomy. Our first simulator was designed by transforming the contents of the video tutorials into an interactive system that could both convey information as well as interactively train the user with the necessary skills. Our resulting VR system trained students on key surgical steps based on five primary steps (Figure 4) as stated below:

- Step 1: Abdominal incisions and insertion of trocars.
- Step 2: Umbilicus incision.
- Step 3: Insertion of the Veress needle through the *linea alba* (abdomen) and peritoneum.
- Step4: Insert the 10mm trocar port toward the pelvis.
- Step 5: Grasp the infundibulum with the forceps to open the peritoneum.

For training, the student positions himself or herself in front of the Kinect sensor while facing the VR graphical display. At this point, the user's body image is projected onto the VR environment and the user's hand motions are mapped into the motion of the virtual surgical tools (Figure 5) as shown in Figure 6 and 7. Each of the aforementioned steps has sub-steps that the user is required to fulfill by manipulating the virtual tools with respect to the patient-displayed anatomy. When sub-steps are completed, a graphical check is displayed on the virtual interface as shown in Figure 8. To provide 'touch-based' feedback, a haptic feedback signal was provided to indicate either a point of penetration (negative feedback) or indicate achievement of a goal (positive feedback).

Figure 4. Key steps of laparoscopic cholecystectomy as displayed in the VR Simulator.

Figure 5. Virtual tools for display on our simulation GUI.

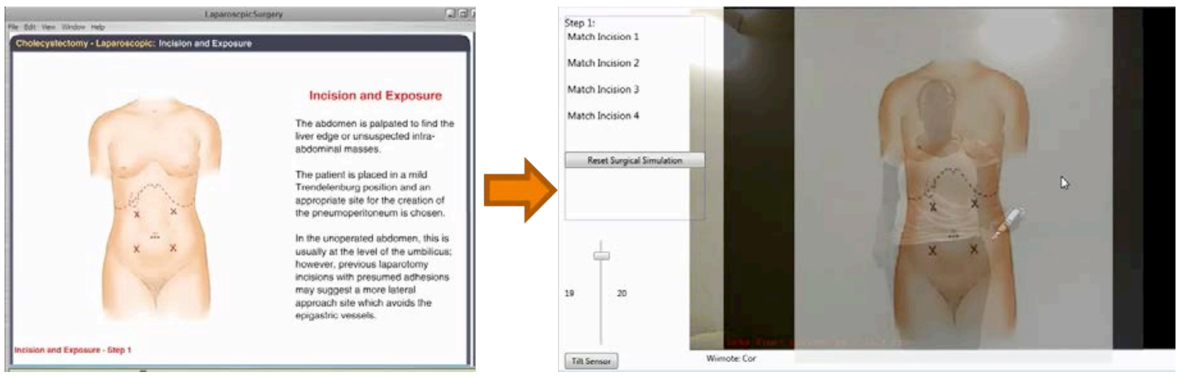


Figure 6. Original video (left image) transformed into an interactive virtual simulator (right image). The user is overlayed onto the virtual surgical scene in a half-transparent fashion, and the tools follow the hand-motion of the user.

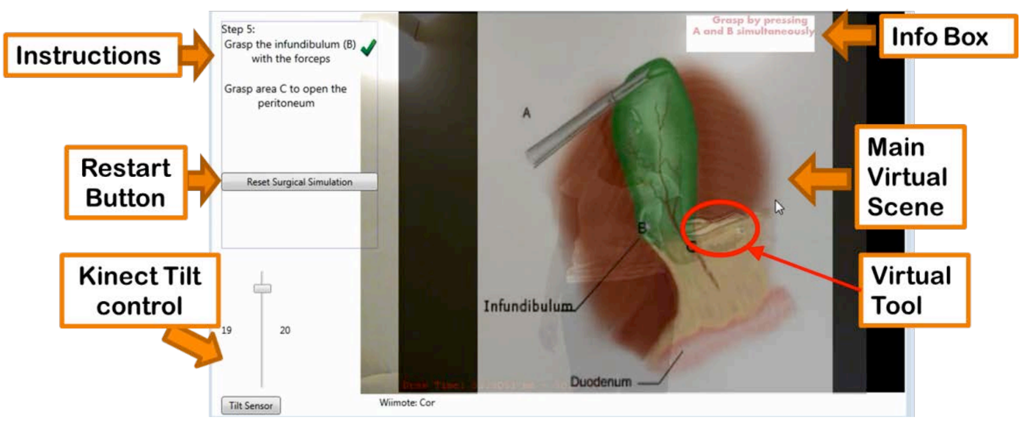


Figure 7. The main control elements of the VR Surgical Environment

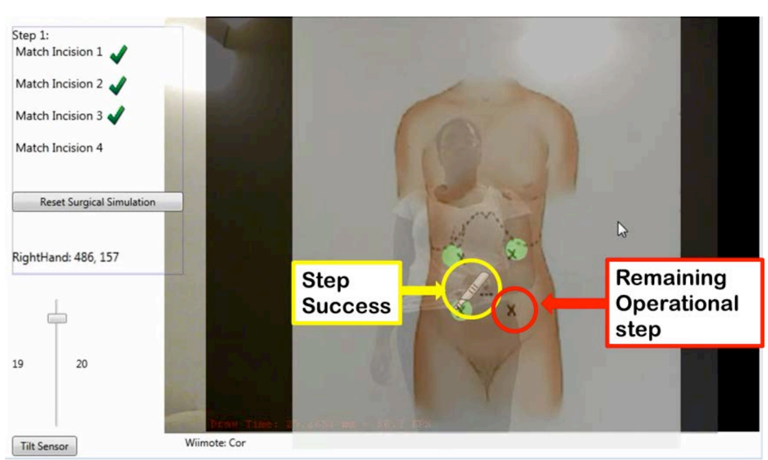


Figure 8. Interactive progress display of sub-steps.

The performance of this initial prototype can be seen in the video file: "Prototype_Demo.avi". After evaluating this prototype with the surgeon and a small pilot of students, we concluded that this prototype might be useful in tutoring on general concepts, but it was insufficient for training students on the high-level skills required for performing the cholecystectomy operations.

B. VR-in-a-Box: Surgical Simulator – Final Design

Based on the evaluation of our first prototype design, our final design consisted of a system that could interactively train medical students with actual video taken from the endoscope during real cholecystectomy operations. Instead of simple pictorial tutorial contents used in the development process of our first prototype, we acquired real video of cholecystectomy surgeries: http://www.youtube.com/watch?v=7tTGfYCqH5w and http://www.youtube.com/watch?v=L7eKRHZjem0. The first video, which was approximately 2 minutes and 30 seconds long, was video taken from the endoscope that displays real imagery of a patient's intestines and tissues as well as the movement of an experienced surgeon's trocar manipulation. Although the second video is an animated 3D graphic simulation, it presents a clear view of the tools and realistic motion of tissues in a simplified view focused on the ball-gladder. To provide more realistic and detailed information on every step of the surgery through our simulator, we analyzed the first video to define 15 key stages (Table 1) and related sub-stages for each stage. Every image frame corresponding to the key stages and sub-stages was captured. After the key stages were defined, we further analyzed the video to extract the surgeon's actions applied using the surgical tool for each key stage (and sub-stage).

Table 1. Key operational states and required actions to complete the stage analyzed from the cholecystectomy video.

State	Operation Description	Required Action
1	Trocar Insertion & Elevate Gall-bladder	Grasp 'infundibulum' and pull to the left
2	Cut adhesion tissue	Cut through adhesion tissue with the right trocar
3	Reveal arteries	Scratch out adhesive tissues
4	Expand the split between the arteries	Cut through between two arteries and expand the split
5	Clip the cystic artery	Clip 3~4 locations of the artery
6	Clip the vile duct	Clip 3~4 locations of the artery
7	Cutting cystic artery	Cut the artery by lifting up in between the clips
8	Cutting vile duct	Cut the artery by lifting up in between the clips
9	Apply heat without char (skipped)	
10	Open up peritoneum	Poke & Expand the hole by pulling sideways
11	Dissect along the edge of the gall-bladder	Using the 'Cradle-and-cut technique'
12	Precise dissection stage	Using the 'Cradle-and-Cut' technique
13	Finish dissecting the gall-bladder	

14	Coagulate bleeding spots.	Apply heat on bleeding spots
15	Take out the gall-bladder through the trocar port	

After the surgical steps were analyzed and defined, we designed a software structure called the *automata model* that encapsulated the details (image sequences, key actions, spots for operation action, etc.) of each stage. The details of this algorithm are further explained in Section V. The automata model is composed of multiple connected automatons. Each automaton corresponds to each key stage, and the simulation progresses as the automaton switches to the next automaton. In essence, each automaton is in charge of 1) displaying the key image frames to the user, 2) tracking and recognizing the user's hand motions, 3) comparing the user's motion with the right action (expert surgeon's movement) at that stage, and 4) implementing follow-up actions according to achievement of the goal (e.g. transition back one sequence if failure, play corresponding video frames in case of time-out, and progressing to the next stage when the correct action is accomplished).

For our final version of the VR-in-a-Box: Surgical Simulator, we upgraded the virtual environment to show both the interactive view composed of key image frames and the user's virtual tools (on the left side) and the tutorial video (on the right side) as displayed in Figure 9. A training session begins by playing the tutorial video (the first video specified in this section), which depicts to the user the real-world surgical steps of the operation along with verbal explanations.

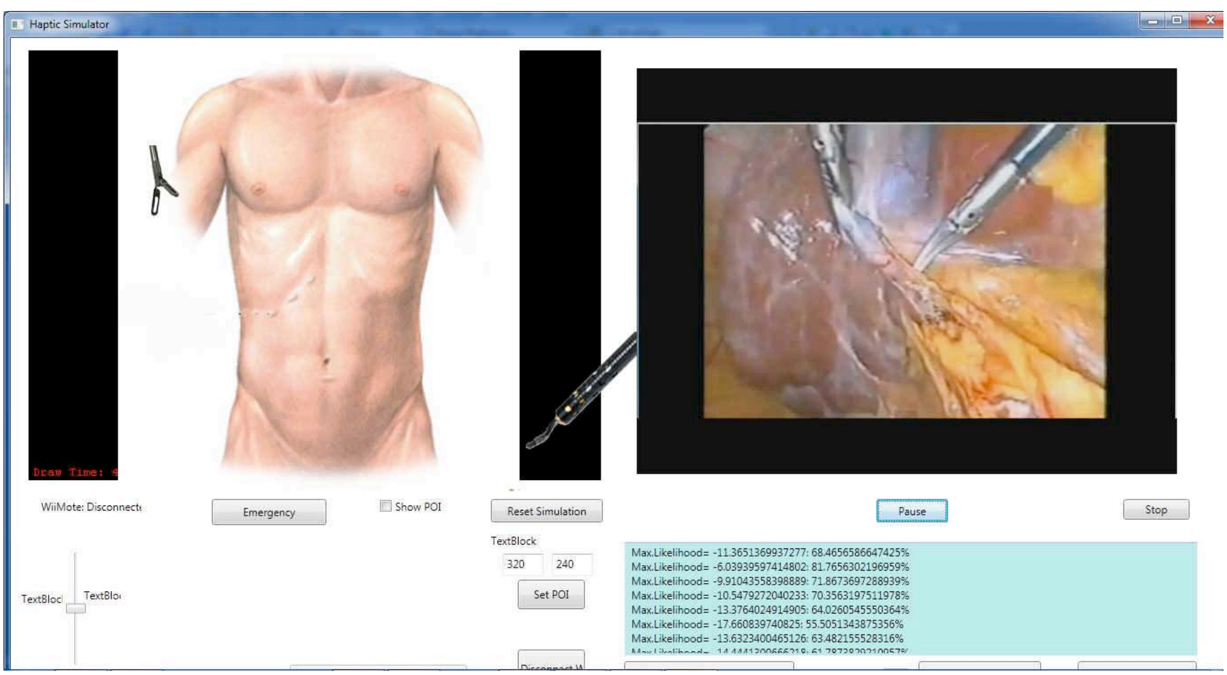


Figure 9. Final design showcasing our VR Surgical Simulator.Figure 5. Virtual

Once the user finishes watching the training video, the user positions himself or herself in front of the Kinect sensor. The system then initiates the automata model by activating the first automaton, which displays the key image frame and starts tracking the user's motion. The user's virtual operations are then compared to the expert's predefined motion to determine success or failure (as explained in Section V). While the user manipulates the virtual surgical tools, descriptions on the previous and current operational stages as well as the required action are depicted on the right side of the display (Figure 10). For novice users, the region (called the point-of-interest (POI)) where the user needs to first place their surgical instrument for achievement of the current surgical operation is highlighted with a "red" circle as shown in Figure 11.

Whenever the user takes action on the POI for each stage (each sub-stage in one stage can have different POIs), the system notifies the user with a short vibration on the Wiimote and starts tracking the motion. If the user takes the "right" action in a given time limit, the system will give the user a positive feedback with a sound, and the automata will progress to the next stage (or sub-stage) of the operation by displaying the next key image frame. If the user does not take the necessary action for the stage in a given time limit, the system will determine that the user is not fully knowledgeable about the current operational step and will play the video associated with the corresponding surgical step (Figure 12).

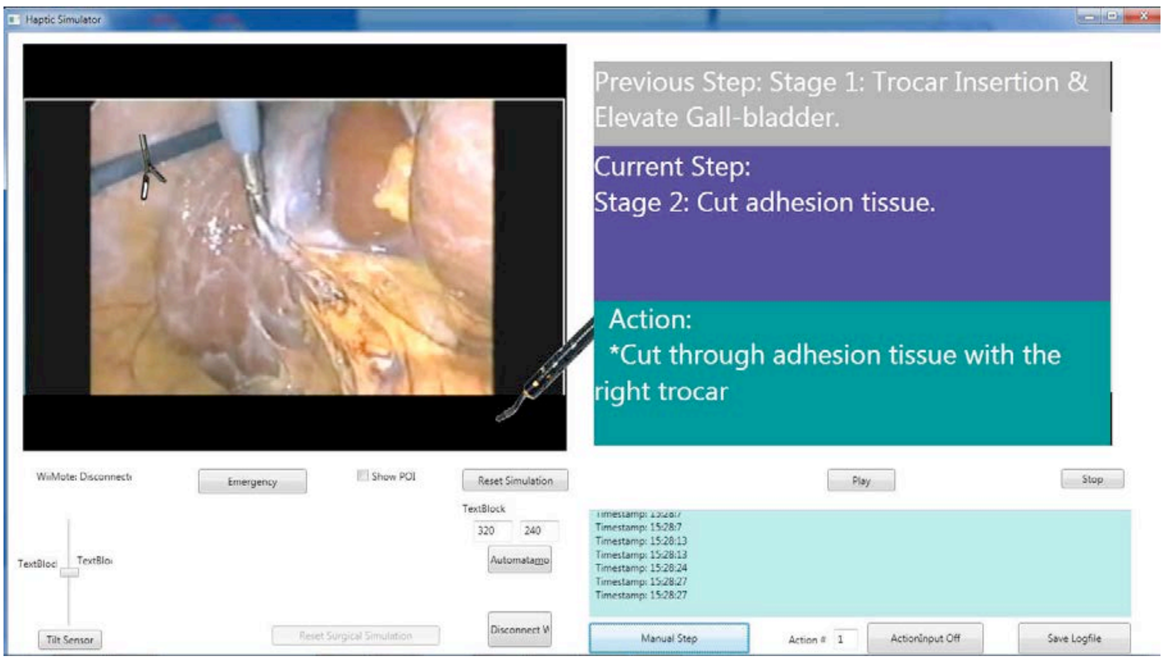


Figure 10. Interactive session with a key image frame and virtual-tool movements. The descript-ions on the previous and current operational stages as well as the required action are displayed on the right side.

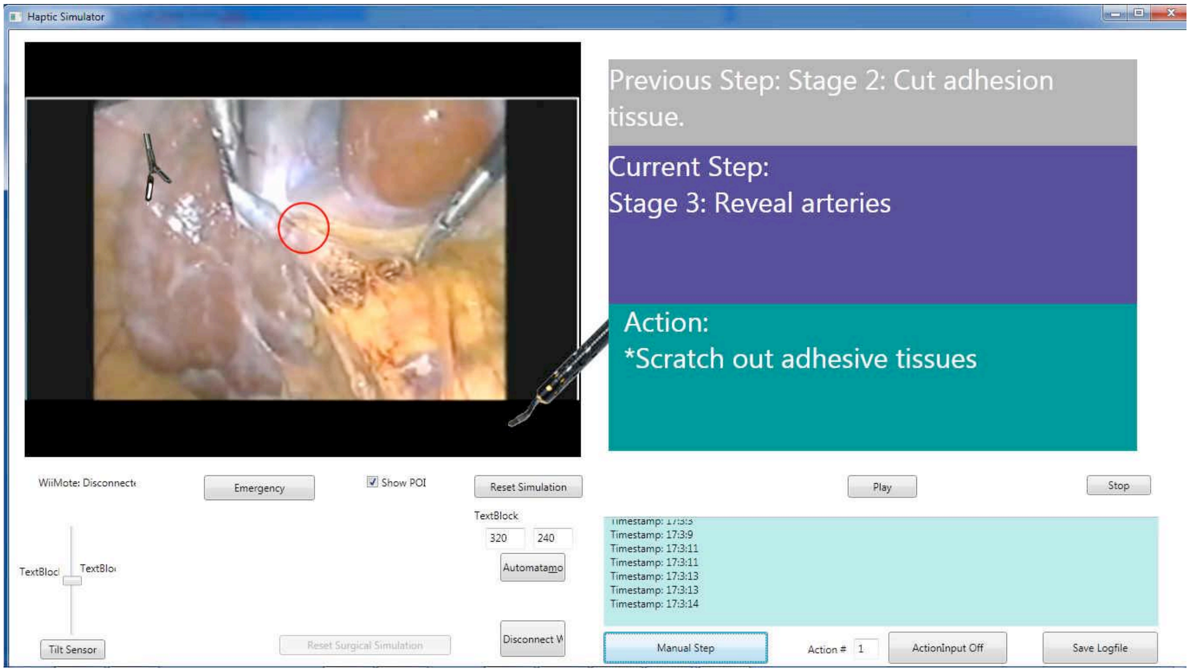


Figure 11. Red circle is placed on the point-of-interest (POI) for novice users.

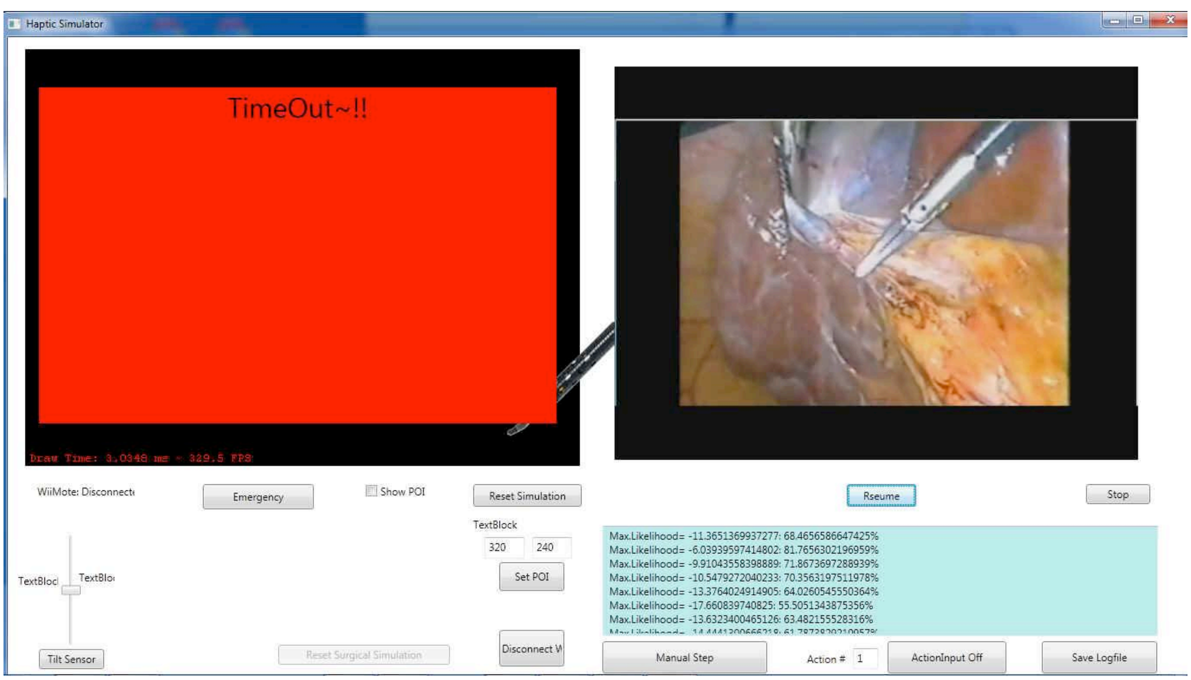


Figure 12. Video tutorial mode for the corresponding stage in case of a “time-out”.

V. ALGORITHMS

For real-time interaction with the user for our surgical simulator, the system needs to constantly determine two categories of information. First, the system is required to track the human's hand-motions (both left and right hands) and determine if their motion is the correct motion related to the current stage (i.e. surgical step). Secondly, the system needs to keep track of the progress of the user in the scope of the full operational sequences and provide the correct set of sequences (e.g. transition to the next stage or change to tutorial-video mode). This section presents the details of the underlying algorithms applied for the determination of the user's motion and the operation of the simulation system.

A. Hidden-Markov Model

The *Hidden-Markov-Model* (HMM) is a well-established statistical model that can analyze a sequence of data and interpret the internal "hidden" relations between the elements in the sequence [12,13]. The HMM assumes a Markov model composed of interconnected "hidden" states, observations, and state transition probabilities as depicted in Figure 13. If a HMM model is predetermined, the HMM model can determine the maximal likelihood between the original training data and a new observation data, and tell if the new data fits the model. If the model is not given but the number of internal states can be estimated, the HMM model can also estimate the probability transitions given specific observation data using Baum-Welch algorithm. The data can either be continuous or discrete, each resulting in continuous HMM model or discrete HMM model.

Although a surgical operation may consist of many different steps—such as preparing surgical tools, inserting trocars, and injecting medicine—each surgeon performs these operations in their own *stylistic* manner. However, there are key surgical steps that are basically defined for the essential parts of the surgery, for example, revealing cystic artery, cutting out vile-duct, and coagulating bleeding spots. These essential operational steps must be performed with accurate speed and trajectories, and the purpose of our simulator is to present the right surgical skills and evaluate the user's (medical student's) learned knowledge in a physical action domain. As such, we devised a method to compare the expert's (surgeon's) operational sequences with the user's (student's) performance to evaluate their learning using the HMM algorithms.

Specifically, we associate the motions of a user's two hands with the virtual movements of surgical tools in a simulator, and represent the user's motions with discrete valued sequences. When a user performs a surgical operation, we need to focus not only on the trajectory of the motion, but also the speed variances of the motion to accurately compare it with the expert's motion. To efficiently perform discretization while capturing both characteristics, we observe the speed variations of the user's hand motion with regard to directions on the two-dimensional domain as visualized in Figure 13 and transform it into a sequence of nine integer values: $\{0,1,2,3,4,5,6,7,8\}$. Figure 14 illustrates an example sequence captured from the cystic artery cutting motion.

We assume each HMM model is composed of eight hidden states, and train the HMM model with a training sequences using Baum-Welch algorithm to best estimate the transition probabilities. Each HMM model is trained on the training data for each action sequence, which is to be performed by an expert surgeon. Since the human-motion tracking data from the Kinect sensor can contain noisy estimations, we collected three sets of data per each action sequence. This enables us to defined 11 different actions required for the cholecystectomy as shown in Table 2.

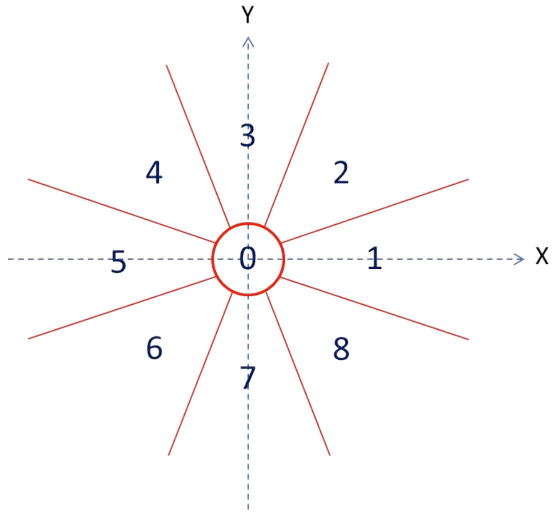


Figure 13. Discretization of hand-motion in the speed domain. ‘0’ region represents the user’s hand is stationary (or almost stationary: intended to filter out ‘noise’), ‘1’ region means the user is moving the hand toward right side on the image, etc.

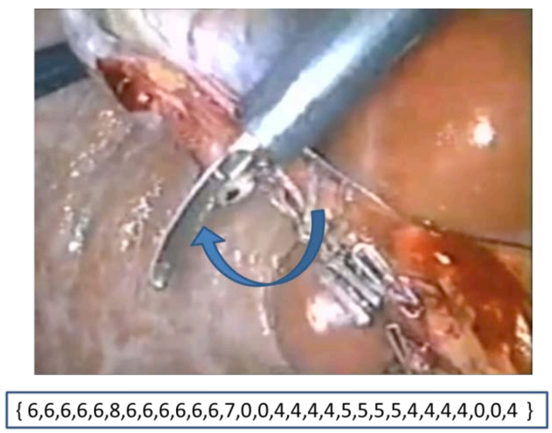
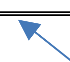


Figure 14. Discretization of a surgical motion during the cutting of cystic artery.

Table 2. Actions recognized as essential operational sequences during cholecystectomy.

Description of Action	Trajectory
Pull with left forceps	
Penetrate tissue with right trocar	
Scratch out tissues	

Clip artery	
“Cradle-and-cut” artery	
Expand hole	
“Cradle-and-cut” peritoneum	
Lift up ball-gladder	
Precise dissection	
Coagulation	
Cut-off ball-gladder	

B. Automata Model

While the HMM model governs the microscopic operation of the tracking and determination of human motion throughout the interaction period, the automata model is in charge of the macroscopic operation of the system. The *automata* is a well-established theoretical model that describes the higher-level states of the system and transitions in a dynamic operation [14]. The automata consists of nodes (automatons) and branches (transition links) in general. In our system, we have defined 15 sequential stages of operation (Table 1), and thus we define an automata model with 15 automatons as illustrated in Figure 15.

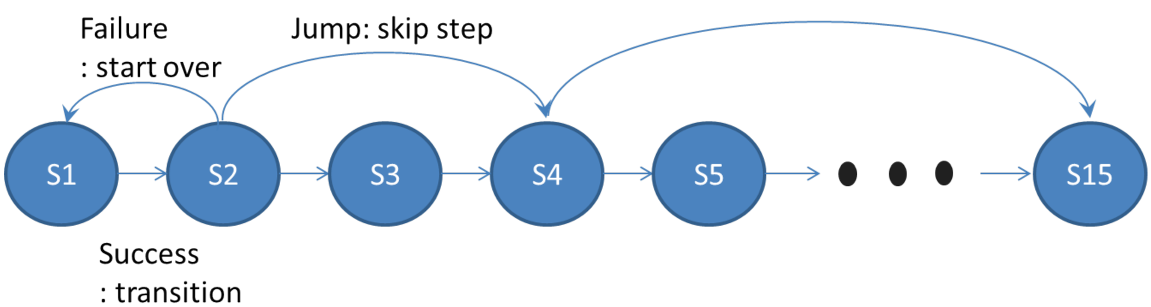


Figure 15. The automata model for our cholecystectomy simulation.

Each automaton defines the surgical stage of the cholecystectomy operation, i.e. the key frame images, the required action sequences, the number of repetition required to finish the stage, and the POIs for the actions. The interesting aspect of the automaton in our system is that, as visualized in Figure 16, each automaton is in charge of training the user with the details of the specific stage of the operation. Specifically, if the user takes the right actions on the POIs in a given time limit, it will mark the stage complete and transition to the next stage determined in the automata. However, if the user does not satisfy the time limitation or perform the right actions, it will stop the simulation and play the tutorial video corresponding to the operational stage (Figure 16). Throughout this closed-loop process of human in the training loop, each automaton can accomplish the goal of training the user through each stage of the operation. For example, if the user is at State 1, the simulator will monitor the user's left hand motion and start saving sequence when the user starts from the POI correlated to the state. If the motion matches with the trained HMM and identifies it as "Grasp 'infundibulum' and pull to the left," then the system will proceed to State 2. If the action is not correctly matched and the time limit is reached, the simulator will stop tracking the user's motion, show a red banner with a "Time out" mark on the left side, and start playing the video sequence for State 1. After playing the specific part for State 1, the simulator will show the simulated scene on the left side again with tools, and start tracking the user's motion again.

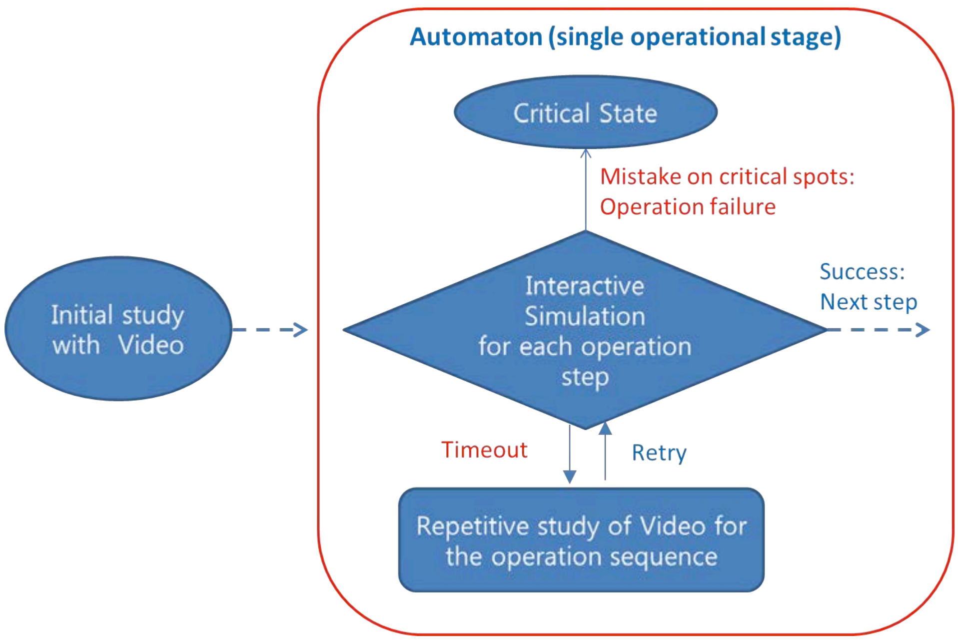


Figure 16. The operation of each automaton.

VI. EXPERIMENTAL STUDY

A. Study Design

We designed an experimental study with human subjects to evaluate the performance and effectiveness of our system in the learning of the cholecystectomy operation. The protocol for the experiment was as follows:

1. Subjects were briefly introduced to the concept of cholecystectomy operations and the purpose of this experiment.
2. Subjects watched the first half of the cholecystectomy video tutorial (approximately one minute).
3. Subjects were briefly introduced to the VR surgical simulator (sensor, haptic and sound feedback, and the message guidelines on the GUI) and shown how to control the virtual tools

4. Subject used the VR surgical simulator to train on the surgical steps of the cholecystectomy operation (State 1 through State 6).
5. Subjects were allowed to stop the training at any time and the log data is saved.

The experiments were designed to be repeated three times with at least an hour interval between experiments per subject. The measurements and evaluation criteria are discussed in the following section.

B. Evaluation Criteria

The details on the recruited human-subject group and the evaluation criteria are described below.

B.1. Participants and Procedures

Six student subjects were recruited for this study. All were novices in medical surgical operations. The age distribution was between 28~36; five were male and one was female. Each experiment per person took less than five minutes, and the same experiment was performed for three days with the same human subject group.

B.2. Measurements – Learning Effect

All subjects were assessed by determining the learning effect associated with interaction with the virtual simulator. The quantitative data associated with the learning effect was used to answer the specific aim of this study - to provide preliminary evidence on the efficacy of the low-cost VR training system. The specific criteria for measurements are as described below:

1. Simulator trial time: The total simulation time after watching the video tutorial is measured in seconds over the three trials (1^{st} day, 2^{nd} day…). The purpose of this measurement is to monitor the user's adaptability on the simulator system, i.e how easily the user learns to use the system.
2. Number of tutorial video parts (due to "time-out") played per trial: By monitoring how many time-outs occur on each operational step, we can measure how fully and specifically the user has gained knowledge on the entire operation.
3. Successful recognition rate of each action by the simulator: By observing the recognition rate of the user's motion with HMM modules, we can gain quantified estimation of how well the user is trained with specific operational skills.

VII. OUTCOME AND RESULTS

This research examined the efficacy of a low-cost VR system on improving surgical laparoscopic cholecystectomy skills and provided a preliminary evaluation of the learning effect.

A. Human Subject Data

A total of six subjects fully participated in the experiments. As described in the previous section, we collected measurements for the number of tutorial video play times per states, number of trial motions per surgical action steps, and total simulation time (measured per states). The typical data collected from a subject per trial is as shown in Table 3.

Table 3. Typical data collected from a human subject with one trial run of our simulator system.

Subject 2	Tutorial On (#)	Actions (# of Trials per Action)			Time (sec)
Trial 1		step1	step2	step3	

State1	0	1			9
State2	2	25			48
State3	1	18	4	20	73
State4	1	1	2	1	13
State5	0	2	1	3	20
State6	0	3			7
Total	4	81			170

B. Simulator Trial Time

Simulation time for each subject to finish States 1 through 6 was measured to determine how well the user adapts to the system, i.e. how easy the system is to learn to use. The results in Figure 17 and Table 4 shows that users took, on average, 4 minutes and 30 seconds to complete (with a standard deviation of 130 seconds), but after two more trials the average time decreased to 1 minute and 15 seconds (with standard deviation of 13 seconds). This presents preliminary evidence that the users can easily learn to use the system and increase their performance.

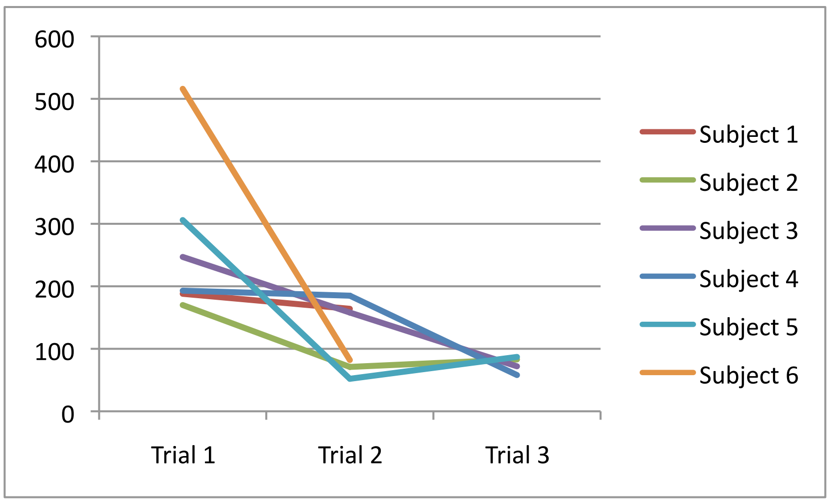


Figure 17. Simulation time of subjects per trial (unit=seconds).

Table 4. Simulation Time of Subjects per Trial (unit=seconds).

Subject #	Trial 1	Trial 2	Trial 3
1	188	164	
2	170	71	83
3	247	158	72
4	193	185	58
5	306	52	87
6	516	82	
Average	270	118.67	75
Standard Deviation	130.38	56.68	12.99

C. Number of Tutorial Video Played per Trial (Due to "Time-out")
The number of tutorial video modes activated during the subject's trial was monitored to estimate how well the subject understands the operational steps for the surgery. Initially, the subjects displayed hesitations in their actions due to incomplete knowledge on the surgical steps, which resulted in about 6.5 tutorial modes being activated on average (with standard deviation of 5.54 times). However, after two more trials, the subjects almost mastered the knowledge on the surgical steps and finished the states with only 0.5 times of tutorial video being activated (with standard deviation of 0.58 times).

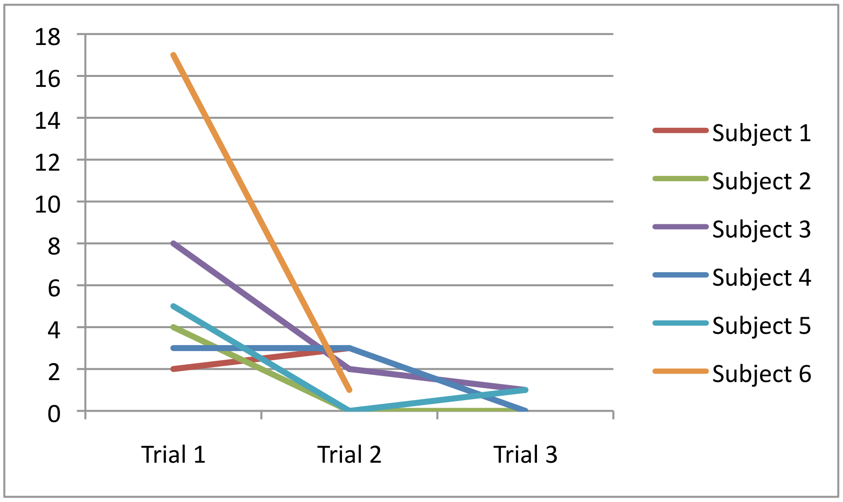


Figure 18. Number of tutorial video modes activated per subjects.

Table 5. Number of Tutorial Video Modes Activated per Subjects.

Subject #	Trial 1	Trial 2	Trial 3
1	2	3	
2	4	0	0
3	8	2	1
4	3	3	0
5	5	0	1
6	17	1	
Average	6.5	1.5	0.5
Standard Deviation	5.54	1.38	0.58

D. Successful Recognition Rate of Each Action by the Simulator
The average number of actions per one surgical step was accounted to analyze how accurate the subject has learned the skills needed to complete the surgical steps. A total of 12 surgical actions were required to complete States 1 through 6. The total action performed by the subjects was determined. On average, the subjects executed about 7.24 actions to complete one correct action at the initial trial. However, after two

more trials, the subjects could complete each surgical step in only 2.3 trials (with standard deviation of 0.55).

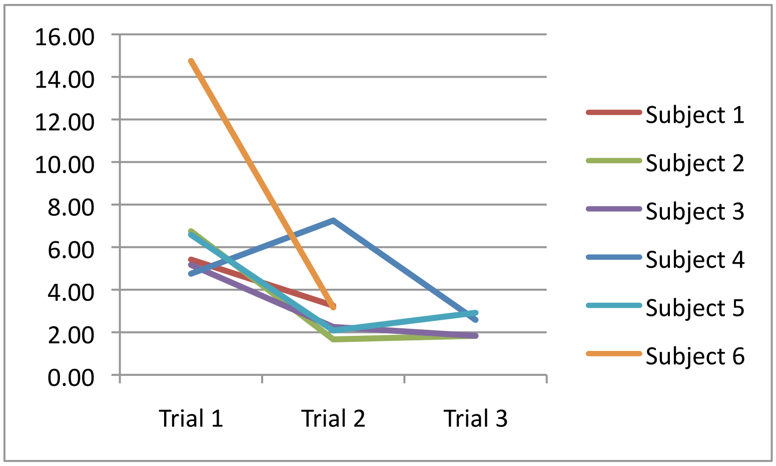


Figure 19. Average number of actions per one surgical step.

Table 6. Average Number of Actions per One Surgical Step.

Subject #	Trial 1	Trial 2	Trial 3
1	5.42	3.25	
2	6.75	1.67	1.83
3	5.17	2.25	1.83
4	4.75	7.25	2.58
5	6.58	2.08	2.92
6	14.75	3.17	
Average	7.24	3.28	2.29
Standard Deviation	3.77	2.04	0.55

VII. CONCLUSIONS

This research examined the efficacy of a low-cost VR system on improving surgical laparoscopic cholecystectomy skills and provided preliminary evaluation of the learning effect. The key element of this research was to design a low-cost VR system that could function as an in-home training system for students. Given that most students possess a computing platform, the resulting cost of the system totals $250 in peripherals (Kinect and Wiimote). In addition, we wished to provide evidence that the VR-in-A-A-Box: Surgical Simulator could improve surgical laparoscopic cholecystectomy skills outside of the training facility. By examining the learning effect on novice users, we have validated that the final version of the VR simulator not only reduces errors in the steps required to perform the procedure but decreases the time necessary for completing the operation. These are key features required for providing evidence on the efficacy of a low-cost VR system. Future efforts include expanding the number of stages used in evaluating the training outcomes, exploring the inclusion of training on other skill-sets, and providing a post-experiment questionnaire the provides user feedback on their perception, as compared to the qualitative results on performance. The results from this study will not only be disseminated through a written publication within the year, but this study will lay the groundwork for securing additional funding through NSF and NIH, both of whom will be pursued – NSF for funding to design adaptive Virtual Reality training systems for individualizing the learning cycle and NIH for conducting a full clinical effectiveness study with the developed technology.

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